A COMPREHENSIVE COMPUTER MODEL FOR PREDICTING DYNAMIC SUBSIDENCE FOR LONGWALL OPERATIONS

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ABSTRACT

This paper presents a number of mathematical models for predicting the different phases of the complete surface subsidence process associated with underground longwall mining. A computer program developed based on the mathematical models is briefly introduced.

INTRODUCTION

In association with underground coal extraction, surface subsidence occurs. Before a final subsidence basin is formed, the surface experiences a complicated subsidence process. The movement and deformation in the subsidence process often cause damage to surface and sub-surface structures. In the process of assessing the damage potential and then designing and implementing effective protective measures for the structures, it is more important to have accurate information of the dynamic subsidence process in the concerned surface area than the final subsidence alone.

In order to understand the full process of surface subsidence associated with underground longwall mining and to develop the prediction method, the authors have conducted an extensive subsidence monitoring program over a large number of longwall panels and collected numerous subsidence data from coal mines and from literature. Based on the data, a number of mathematical models have been developed for predicting the different phases of the complete subsidence process associated with underground longwall mining. A computer program DYNSUB is also developed to facilitate the subsidence prediction.

This paper presents the mathematical models and the computer program for predicting the complete subsidence process. Two cases of applying DYNSUB are also presented.

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SUBSIDENCE PROCESS ASSOCIATED WITH LONGWALL MINING

Longwall mining method is a highly productive, safe and efficient method used for underground coal extraction. In the U.S.A., the common practice is to separate the adjacent longwall panels by rows of unmined coal blocks of sufficient dimension called chain pillars. The chain pillars and their associated entries and crosscuts between two adjacent longwall panels are called a chain pillar system. A longwall section consists of a number of longwall panels adjacent to each other and surrounded by barrier pillars of large dimension and main and submain entries.

As the mining proceeds in a longwall panel, the overburden strata as well as the ground surface experiences a complicated subsidence process. When a sufficient amount of time has elapsed after mining, a final subsidence basin forms over the mined area. The complete surface subsidence process associated with longwall mining is briefly described as follows.

In the initial stage of mining a longwall panel, there is no subsidence or subsidence is very small as compared to the final amount to be subsided until the face has advanced a critical distance away from the panel setup entry. This critical distance is called subsidence initiation distance. Thereafter, a fairly rapid subsidence process will follow. The thinner the overburden is, the faster the subsidence process will be. The process gradually slows down as the face continues to move forward. This process is called the subsidence initiation and development process. The occurrence of this process is mainly due to the bridging effect of the overburden strata.

After the longwall face has past a distance of about 1.5 to 2 times of the overburden depth depending on the face advance rate, that portion of the surface dynamic subsidence basin on the side of the advancing longwall face travels in the same pace with the face while retains the same shape provided that the face advances at a fairly constant rate. This process is called the normal subsidence process.
When the longwall face stops advancing either due to a vacation or panel completion, the surface subsidence basin will gradually change its shape from a shape determined by the normal dynamic subsidence process at the time of face stoppage to its final shape long after mining. This process is called residual subsidence process.

If only one panel is mined, the shapes of both dynamic and final subsidence basins are generally symmetric about the panel longitudinal center with very small amount of subsidence occurred above the unmined area. However, as two or more adjacent panels in a longwall panel are mined, this is no longer true for most cases. When the overburden is thick and the total width of the chain pillar system is small, a large amount of subsidence occurs over the chain pillar between the mined longwall panels as compared to the subsidence over the center of the mined panels. It is believed that the additional subsidence is caused by the convergence of the chain pillar system (Luo and Peng, 1990).

**MATHEMATICAL MODELS**

The computer program DYNUSUB is developed based on a number of mathematical models. The details of the model development can be found elsewhere (Peng and Luo, 1988; Luo, 1989; Luo and Peng, 1990 and 1991). A brief description of each of the mathematical models is presented in this section. It should be noted that all the mathematical models are capable of predicting surface subsidence (S), horizontal displacement (U), slope (i), strain (ε) and curvature (κ) at any point in the subsidence basin. However, only those formulae for calculating subsidence are presented in this paper.

**Prediction of Final Subsidence**

As it will be stated later, final subsidence is the most important component in each of the mathematical models for predicting dynamic subsidence process. Therefore, accurate prediction of final subsidence at any point of the subsidence basin plays a crucial role in the prediction of dynamic subsidence. The amount of final subsidence at a surface point is not only affected by the extraction of coal in the longwall panel beneath the point but also by those in the other mined panels in the same longwall section and the convergence of those chain pillar systems on both sides of which the panels have been mined. Therefore, the prediction method for final subsidence should be able to deal with both mining of a single longwall panel and that of multiple panels in a longwall section.

**Mining of a Single Panel**

After the coal extraction in a single longwall panel, an elliptic or rounded-corner-rectangular shaped final subsidence basin will form over the mined panel (Peng, 1992). One of the influence function methods, the knothe's theory (Knothe, 1957), is employed for predicting final subsidence due to mining of a single panel. The underlying principle of this theory is that the extraction of an elemental area of coal seam will cause surface to subside. The amount of subsidence at a surface point due to the extraction of this coal element, called elemental subsidence, is inversely exponentially proportional to horizontal distance between the surface point of interest and the extracted element. Final subsidence at a surface point is the summation of all the elemental subsidence caused by mining the entire area element by element, or in mathematical form:

\[ S(x, y) = m \cdot a \cdot f(x, y) \]  \hspace{1cm} (1)

where
- \( m \)- mining height
- \( a \)- subsidence factor
- \( f(x, y) \)- subsidence distribution function, which is

\[ f(x, y) = \frac{1}{A} \int_{A} \frac{A_{xy}}{2} \; dx \; dy \]  \hspace{1cm} (2)

where
- \( A \)- computing area for the mined longwall panel which is defined by integrating a distance equivalent to the offset of inflection point (d) from the panel edges inwards
- \( R \)- radius of major influence
- \( x', y' \)- local coordinates of the center of the extracted element with the origin of the local coordinate system located at the surface point of interest.

**Mining of Multiple Panels**

When two or more panels in a longwall section are mined, additional subsidence induced by the convergence of those chain pillar systems between the mined longwall panels has to be considered. A mathematical model has been proposed by Luo and Peng (1990 and 1991) for predicting the subsidence due to the convergence of the chain pillars. The final subsidence at a surface point can be calculated by superimposing the additional subsidence on those caused by mining of the longwall panels without considering the convergence of the chain pillar systems. The additional subsidence due to the convergence of a chain pillar system is:

\[ S'(x, y) = \Delta S_{max} \cdot f(x, y) \]  \hspace{1cm} (3)
where $\Delta S_{\text{max}}$ is the maximum possible subsidence induced by the convergence of the chain pillars between the mined panels and $f_{x}(x)$ is the subsidence distribution function which is also defined by Eq. 2. Based on the subsidence data collected from about 30 cases, $\Delta S_{\text{max}}$ can be determined by the following empirical formula:

$$\Delta S_{\text{max}} = -0.04903 + 1.45189 \times 10^{-4} \frac{k}{r_{p}}$$

(4)

where $h$ is the overburden depth in meters, $p$ is recovery ratio of the longwall section which is calculated from the panel width ($W_{p}$) and the total width of the chain pillar system ($W_{n}$) as:

$$p = \frac{W_{n}}{W_{p} + W_{n}}$$

(5)

Based on the principle of superposition, the final subsidence at any surface point in the subsidence basin due to mining of multiple panels in a longwall section is then calculated as:

$$S_j = \sum_{i=1}^{n} \left( S_{i} + \frac{1}{2} S_{i+1} \right)$$

(6)

where $S_j$: final subsidence at the point of interest caused by mining of the $i$th longwall panel

$n$: number of longwall panels that has been mined in the longwall section

$S_i$: final subsidence at the point of interest due to the convergence of the $j$th chain pillar system between two mined longwall panels

$k$: number of chain pillar systems on both sides of which the panels have been mined

**Prediction of Dynamic Subsidence**

The dynamic subsidence process includes the following four basic phases: (1) subsidence initiation and development process; (2) normal dynamic subsidence process; (3) residual subsidence process; and (4) dynamic subsidence over chain pillar systems.

**Subsidence Initiation and Development Process**

The subsidence initiation and development process can be divided into two phases, one before and the other after the longwall face has reached the initiation distance away from the panel setup entry. Since the amount of surface subsidence in the first phase is usually insignificant, it can be ignored. Therefore, the key for predicting the subsidence initiation and development process is the determination of the subsidence initiation distance and the dynamic subsidence development process after the face has past the initiation distance from the setup entry. The subsidence initiation distance can be empirically determined as:

$$L_{i} = 10.05 + 0.86 \sqrt{h}$$

(7)

A mathematical model has been developed (Luo and Peng, 1993) for predicting the dynamic subsidence process after the distance between the longwall face and the panel setup entry exceeds the initiation distance. In the development of this model, it is assumed that the subsidence velocity at a surface point at time $t$ is proportional to the difference between the potential subsidence, $S_p$, and the actual subsidence, $S$, at this point and at this time, or

$$\frac{\partial S}{\partial t} = c(S_p - S)$$

(8)

where $c$ is the coefficient of subsidence that is related to the overburden depth and can be determined by the following empirical formula:

$$c = \frac{1.2982}{h^{0.67}}$$

(10)

**Normal Dynamic Subsidence Process**

When a longwall face maintains a fairly constant advance rate, the distribution of the subsidence velocity along a longitudinal line over the panel assumes the shape of the normal probability distribution function (Peng and Luo, 1988; Luo, 1989) as shown in Fig. 1. The peak subsidence velocity is $v$ distance behind the advancing longwall face, and subsidence is barely detectable at a distance $l$ ahead of the face. Through some manipulations, the mathematical expression for predicting normal subsidence at a surface point is obtained as:
where $S_f$ is the final subsidence at the point of interest. The parameters $I$ and $I_1$ are functions of the overburden depth $(h)$ and the average face advance rate $(v)$, and can be determined by:

$$I = (0.223 + 0.0331 \sqrt{v})h$$
$$I_1 = \frac{0.133}{1 + 0.35v}$$

**Residual Subsidence After Face Stop**

A mathematical model has been proposed for predicting the residual subsidence process after the longwall face stops advancing (Lao and Peng, 1991). In the development of the model, it is assumed that the subsidence velocity at a surface point at time $t$ is proportional to the amount of subsidence to subside thereafter, that is, the difference between the final subsidence and the actual subsidence at time $t$. If the advance rate of the longwall face before it stops is fairly constant, the amount of subsidence at the surface point of interest when the face stops can be determined by Eq. 11 as $S_f$. The subsidence at the point after the face has stopped for $t$ days is:

$$S(t) = S_f - (S_f - S) e^{-ct}$$

where $c$ is a coefficient which is also evaluated by Eq. 10

**Dynamic Subsidence over Chain Pillars**

The subsidence data collected by the authors also indicates that the dynamic subsidence process induced by convergence of the chain pillar systems between longwall panels can be predicted in the same way as the dynamic subsidence processes (Eqs. 9, 11 and 14) over a operating longwall panel. One example of comparison between the normal dynamic subsidence process over an operating longwall panel and that over a chain pillar system is shown in Fig. 2. The overburden depth in the study site was 223 m and the average face advance rate was 15.5 m/day. Daily subsidence monitoring was conducted during the active subsidence period. The measured subsidence data at about 30 monuments were divided into two groups, one over the longwall panel and the other over the chain pillars. Subsidence at each of the monuments at a given time is normalized against its final amount. The average, lower bound and upper bound were calculated for each of the two groups and plotted against the distance that the longwall face has past from the point of interest along the mining direction (Fig. 2). It shows that the subsidence development curve for those points over chain pillars closely follows that for the points over the longwall panel. Therefore, the dynamic subsidence process due to convergence of a chain pillar system, $S'$, can be predicted in the similar way as that over an operating longwall panel (Eqs. 9, 11 and 14).

In the prediction of dynamic subsidence process due to convergence of a chain pillar system, the chain pillars system is treated as an imaginary longwall gob which produces a maximum possible subsidence of $\Delta S_{max}$ on the ground surface. A dynamic Cartesian coordinate system is used as shown in Fig. 3. The Y-axis overlaps the advancing longwall face. The X-axis is parallel to the mining direction and located in the previously mined panel at a distance equivalent to the offset of inflection point (d) from the panel tailentry. The computing width of the imaginary gob is the total width of the chain pillar system plus an offset of inflection point on the headentry side of the previously mined panel and another on the tailentry side of the operating longwall panel. The final subsidence due to convergence of the chain pillar system at a surface point, $S'$, is calculated using Eqs. 3, 4 and 5. By
Fig. 3 Dynamic Coordinate System for Predicting Dynamic Subsidence due to Convergence of Chain Pillars

Substituting $S$ into one of the formulae for predicting dynamic subsidence (Eqs. 9, 11 and 14), the dynamic subsidence due to convergence of the chain pillar system can be calculated.

**COMPUTER PROGRAM DYNSUB**

A computer program, called DYNSUB, has been developed to facilitate the data input and output and to carry out the computations involved in the prediction of dynamic subsidence processes as the results of underground longwall mining. This program is one of the six modular programs in the computer program package, CISPM (Comprehensive and Integrated Subsidence Prediction Model), developed by the authors (1989). In addition to predicting dynamic subsidence for longwall operations, CISPM is also capable of predicting final subsidence for longwall operations and for irregular (non-rectangular) underground openings, recommending subsidence parameters for new mines based on geological and mining parameters; deducing subsidence parameters from collected subsidence data; and processing subsidence survey data.

Since its first debut in 1989, a number of new features have been added to program DYNSUB. Some of the features of this program are:

- It is capable of predicting the full dynamic process of surface subsidence associated with underground coal mining operation in a longwall section as described in this paper. The first version of DYNSUB was only capable of predicting the normal dynamic subsidence process.
- It requires no in-depth knowledge of subsidence theory to perform a prediction. The input data has been minimized to require only the following information: overburden depth, panel width and length, width of the chain pillar system, mining height, average face advance rate, current face location, and elapsed time after face stops (default is zero).
- The subsidence parameters used in the prediction will be automatically determined by the program. However, the user can input their own preferred parameters.
- It outputs surface movement and deformation indices such as subsidence ($S$), horizontal displacement ($U$), slope ($\theta$), strain ($e$) and curvature ($k$) for up to 800 surface points in a subsidence basin. The surface points can be evenly distributed along a straight line or randomly distributed in an area. At each surface point, the movement and deformation indices can be calculated along any specified direction and/or along their respective principal direction. The output can be in text or graphic formats.
- It requires no special computer knowledge to operate this program. The program is equipped with a carefully designed menu system. It has an easy data input environment. Its on-screen and random access help, operation hints at various levels provide further assistance for the user to understand the theory involved and to operate the program.
- The minimum requirement for the computer system to run this program is an MS- or PC-DOS based computer with: (1) DOS version 2.0 or later; (2) two floppy disk drives; (3) 640 KB RAM; (4) CGA card and compatible monitor; and (5) math co-processor.

**CASE DEMONSTRATIONS**

**Case I**

Figure 4 shows the comparison between the measured and the predicted surface subsidence profiles in the initial stage of mining a longwall panel. The longwall panel was 244 m wide and about 920 m long. The overburden depth was 76 m. A coal seam of about 1.83 m thick was extracted from the panel. The longwall face advanced at an average rate of 7.2 m/day. A line of subsidence monuments was installed along the panel longitudinal center and over the panel setup entry. Daily survey was performed on the monuments.

The dynamic subsidence profiles for three different face locations are predicted using program DYNSUB and plotted in Fig. 4. The three face locations were 68, 78 and 86 m away from the panel setup entry. It shows that the agreement is satisfactory between the predicted and the measured subsidence profiles along a large portion of the subsidence monument line. However, some